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The role of doped layers in dephasing of 2D electrons in quantum well structures

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Abstract. The temperature and gate voltage dependencies of the phase breaking time is studied experimentally in the structures with quantum well based on GaAs/InGaAs. There is shown that arising of the states at the Fermi energy in the doped layers (Sn δ layer in our case) leads to significant decreasing of the phase breaking time and to weakness its temperature dependence.

The inelastic of the electron-electron interaction is the main phase breaking mechanism in low dimensional structures at low temperature. This mechanism predicts divergence of phase breaking time (τ_φ) with decreasing temperature. But unexpected saturation of τ_φ at low temperatures was revealed in recent years in one and two dimensional structures [,]. It is one of reason of the particular interest to the possible additional dephasing mechanisms in such structures.

The analysis of the low field negative magnetoresistance, resulting from destruction of the interference correction to the conductivity, is the main method of determination of the phase breaking time. We report the results of detailed studying of the negative magnetoresistance in gated structures based on GaAs/InGaAs. The heterostructures investigated consist of 0.5 μm-thik undoped GaAs epilayer, a Sn δ-layer, a 60 Å spacer of undoped GaAs, a 80 Å $In_{0.2}Ga_{0.8}As$ well, a 60 Å spacer of undoped GaAs, a Sn δ-layer, and a 3000 Å cap layer of undoped GaAs. The samples were mesa etched into standard Hall bridges and Al gate was thermally evaporated over the cap layer. The gate voltage dependencies of the electron density, conductivity and Hall mobility are presented in Fig. 1 for one of the structures. The low field magnetoresistance for some voltage are shown in Fig. 2. The magnetic field dependencies of $\Delta\sigma(B)$ at $B < 1 - 0.5B_{tr}$, where $B_{tr} = \hbar c/2el^2$, l is mean free path, are well described by the standard Hikami expression [ ]:

$$\Delta\sigma(b) = \alpha G_0 \left[\psi\left(\frac{1}{2} + \frac{\tau_p}{\tau_\varphi}\frac{1}{b}\right) - \psi\left(\frac{1}{2} + \frac{1}{b}\right) - \ln\frac{\tau_p}{\tau_\varphi} \right], \qquad (1)$$

where $G_0 = e^2/(2\pi^2\hbar)$, b is magnetic field measured in units of B_{tr}, τ_p is momentum relaxation time, and $\alpha = 1$ in the diffusion approximation. In [ ] we showed that (1) well describes $\Delta\sigma(B)$ beyond the diffusion approximation also, but with $\alpha < 1$. Thus, one can determine α and τ_φ as fitting parameters, comparing the experimental $\Delta\sigma(B)$ dependence with (1). Note that values of α and τ_φ determined by this way depend on fitting magnetic field range and in Fig. 3 the conductivity dependencies of τ_φ as determined from the different fitting range are presented.

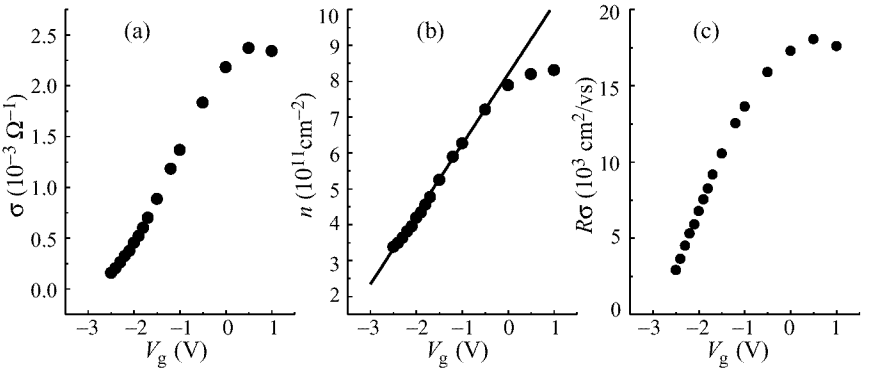

Fig. 1. The gate voltage dependencies of the conductivity (a), electron density (b), and Hall mobility (c) at $T = 4.2$ K. The straight line in (b) is the theoretical total density of the electrons.

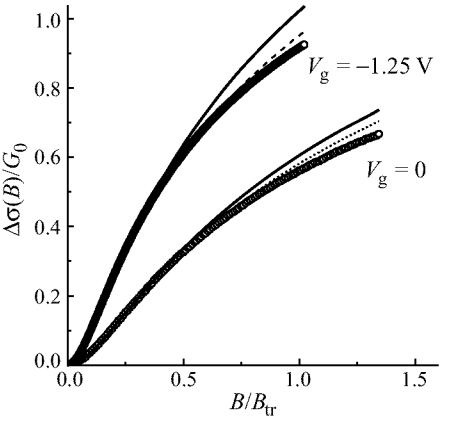

Fig. 2. Negative magnitoresistance at $T = 4.2$ K for two gate voltages. Curves are the theoretical dependencies according to (1) with parameters obtained by the fitting in magnetic field range $0 - 0.25B_{tr}$ (solid curves) and $0 - 0.5B_{tr}$ (dotted curves).

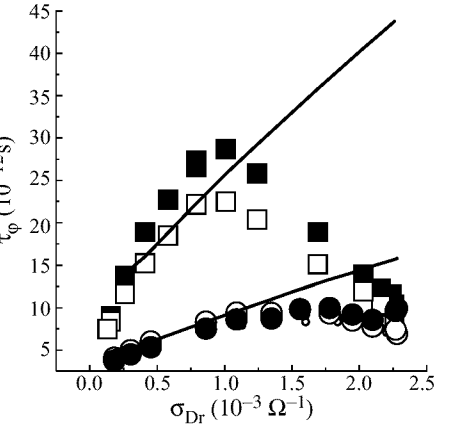

Fig. 3. Conductivity dependencies of τ_φ obtained by the fitting in magnetic field range $0-0.25B_{tr}$ (open symbols) and $0-0.5B_{tr}$ (solid symbols) for $T = 4.2$ K (circles) and $T = 1.5$ K (squares). Curves are the theoretical dependencies given by (2).

When inelasticity of electron-electron interaction is main phase breaking mechanism, τ_φ depends on conductivity and temperature only and for 2D case

$$\tau_\varphi = \frac{\hbar}{kT}\frac{\sigma}{2\pi G_0}\frac{1}{\ln\left(\frac{\sigma}{2\pi G_0}\right)}. \qquad (2)$$

As is seen from Fig. 3 the conductivity dependence of τ_φ is close to the theoretical one when σ varies in the range $(0.2-1.2) \times 10^{-3}$ Ω^{-1}, but significant deviation is evident for larger σ. The temperature dependencies of τ_φ are presented in Fig. 4 for some gate voltage and one can see that τ_φ deviates from $1/T$ dependence just for $\sigma > 1 \times 10^{-3}$ Ω^{-1}.

To interpret these temperature and conductivity dependencies of τ_φ let us analyze the variation of density of electron in quantum well n (exactly this value is determined from the Hall effect and Shubnikov–de Haas oscillation) with gate voltage (see Fig. 1). The

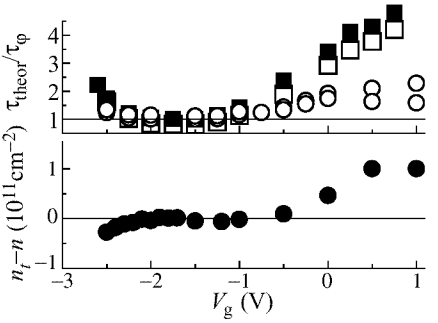

Fig. 4. Gate voltage dependencies of the ratio $\tau_{theor}/\tau_\varphi$ (a) for $T = 4.2$ K (circles) and $T = 1.5$ K (squares). The difference between the total electron density and density of 2D electron in the quantum well as function of V_g (b).

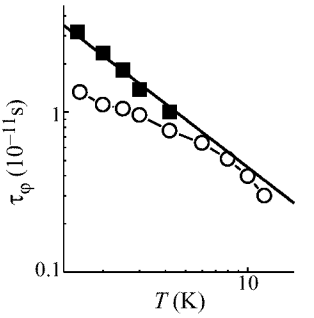

Fig. 5. Temperature dependencies of τ_φ at $V_g = -1.8$ V (squares) and $V_g = +0.5$ V (circles). The line is the $1/T$ dependence.

variation of the total electron density n_t with V_g has to be described by the simple expression $n_t(V_g) = n(0) + Vg\,C/e$, where C is the gate–2D channel capacity per centimeter squared (straight line in Fig. 1(a)). One can see that in the range of V_g from -1 to -3 V the experimental data are close to this dependence, but at $V_g > -1$ V the electron density in the quantum well is less, than the total density of the electrons n_t. It means that at $V_g > -1$ V the fraction of the electrons $(n_t - n)$ occupies the states in δ-layers. From Fig. 4, where the gate voltage dependence of $(n_t - n)$ and ratio $\tau_\varphi/\tau_{theor}$ are presented, one can see that $\tau_\varphi/\tau_{theor}$ deviates from unity when the electrons arise in δ-layers. Thus, appearance of the states in δ-layer at the Fermi energy, and, consequently, the arising of the tunneling of the electrons between quantum well and δ-layer leads to decreasing τ_φ. This interdependence is clear when the phase breaking time of an electron in δ-layer is significantly shorter than that in quantum well. The phase breaking mechanisms in the doped layers, where electrons occupy the states in the tail of density states, are the subject of additional study, but it seems no wonder that dephasing in this layers occurs faster than in quantum well.

In conclusion, the δ- or modulation doped layers are arranged in heterostructures to create the carriers in quantum well or near the hetero-junction. When the states at the Fermi energy appear in the doped layers, the tunneling of the carriers between quantum well and doped layers arises. This process can lead to significant decreasing of the phase breaking time of the carriers in quantum well.

Acknowledgment

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